$T = \frac{3}{2}$ states in mass-11 nuclei*

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A 740-keV-wide peak in the ^{6}He spectrum from the bombardment of ^{14}N by 70-MeV ^{3}He particles is identified as the mirror of the $\frac{1}{2}^-$ first excited state of ^{11}Be. The Q value for the ^{14}N(^{3}He, ^{6}He)^{11}N reaction to this state is -25.03 ± 0.10 MeV, which corresponds to a mass excess of 25.23 ± 0.10 MeV. The analogs of this state in ^{11}C and ^{11}B were observed with the ^{13}C(p, t) and ^{13}C(p, ^{3}He) reactions, and the excitation energies and widths found to agree well with the previous measurements.

[NUCLEAR REACTION ^{14}N(^{3}He, ^{6}He), $E = 70$ MeV measured Q, deduced mass excess of ^{11}N.]

I. INTRODUCTION

The nucleus ^{11}N, which is the mirror nucleus to ^{11}Be, is predicted to be several MeV unbound by Coulomb energy systematics[1] and the Garvey-Kelson mass relations.[2] The ground-state spin of ^{11}Be is $\frac{1}{2}^+$,[3] and an isobaric mass quartet based on this state would be an extremely interesting test of the shell-model description,[4] which includes strong $2s_{1/2}$ particle strength even though the nucleus is located well within the $1p$ shell. However, the mirror of this level in ^{11}N would have a very large width because it can decay very rapidly by an $l = 0$ proton to ^{10}C in its ground state. It is also very difficult to form such a state with, for example, the ^{14}N(^{3}He, ^{6}He)^{11}N reaction since in this case the required $2s_{1/2}$ particle strength is not present in the target.

The first excited state of ^{11}Be has spin $\frac{1}{2}^-$ (Ref. 5) and lies at $E_x = 0.320$ MeV. The analogs of this state are known in ^{11}B and ^{11}C, and the decay of its mirror state in ^{11}N would at least be hindered by the requirement of an $l = 1$ proton decay. In this paper a peak in the spectrum of ^{14}N(^{3}He, ^{6}He)^{11}N is shown to have a width consistent with $l = 1$ decay and an energy in very good agreement with the predictions of the isobaric multiplet mass equation based on the three $T = \frac{3}{2}, \frac{1}{2}^-$ levels in the $A = 11$ nuclei. In addition the cross section for ^{14}N-(^{3}He, ^{6}He)^{11}N has a typical value for p-shell target nuclei. The $T = \frac{3}{2}$ states in ^{11}B and ^{11}C were also studied using the ^{13}C(p, ^{3}He) and ^{13}C(p, t) reactions in order to check the parameters of the known $T = \frac{3}{2}$ levels.

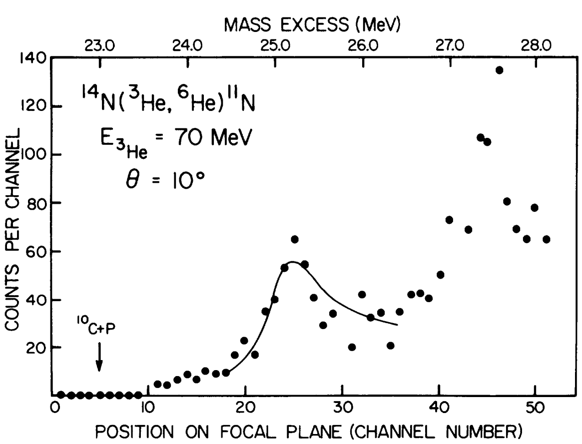

FIG. 1. A composite spectrum from several runs on the ^{14}N(^{3}He, ^{6}He)^{11}N reaction at 70 MeV and 10° (lab). The solid curve is a theoretical estimate of the shape of the ^{11}N peak and is discussed in the text.

II. EXPERIMENT AND RESULTS

A. Search for states in ^{11}N

The ^{14}N(^{3}He, ^{6}He)^{11}N reaction was studied at a beam energy of 70 MeV and laboratory angles of 6, 10, and 13° using a time-of-flight plus magnetic analysis combination which has been previously described.[6] The 10° data were the most satisfactory since they were obtained with a fixed angle gas target arrangement which was designed especially for use in a spectrograph.[7] The 6° data were taken with a 1-mg/cm^2 melamine foil, the uniformity and thickness of which changed during bombardment. The 13° data were taken with a conventional gas target arrangement. The 6 and

13° data are in excellent agreement with the 10° data but have poorer statistics and somewhat less accurate calibrations. The kinematic effects in the $^{14}N(^{3}He, ^{6}He)^{11}N$ reaction are quite marked even at forward angles, and therefore the observation of the same width and energy of a peak at all three angles is a strong indication that a ^{11}N state is being studied.

The spectrum shown in Fig. 1 is a composite of several runs taken at a gas pressure of 200 Torr and a lab angle of 10°. The curve shown on the figure is a theoretical description of the decay width and will be discussed later in this paper. Also shown on the figure is the threshold for the three-body reaction $^{14}N + ^{3}He \rightarrow p + ^{10}C + ^{6}He$. There is an indication of the onset of this process at channel 10, at which point the proton has enough energy to overcome the Coulomb barrier. An interesting feature of the spectrum is the very strong peak at channel 47 which could be the mirror of several excited states at 1.78, 2.70, and 3.41 MeV in ^{11}Be.

The mass scale was determined by comparison to the $^{16}O(^{3}He, ^{6}He)^{13}O$ (for the mass of ^{13}O see Ref. 1) reaction which was produced in the identical gas cell arrangement. The error in this scale is about 30 keV, which is considerably smaller than the uncertainties in determining the centroid of the broad peak. A maximum and minimum smooth background was subtracted from the data in order to obtain the value and uncertainties of the estimate of the width and position of the peak. The level parameters for the peak near channel 25 are mass excess $= 25.23 \pm 0.10$ MeV and $\Gamma = 740 \pm 100$ keV. The cross section at 10° was found to be 0.5 μb/sr. These results can be compared to a previous observation of ^{11}N (see Ref. 8) in which several ^{6}He groups from the $^{14}N(^{3}He, ^{6}He)$ reaction with less than 500-keV width were observed but no mass excess quoted. These data, which were taken at 62 MeV and 11.7°, gave a cross section of 0.050 μb/sr. The instrumental resolution of the present experiment, as measured with the calibration reaction, $^{16}O(^{3}He, ^{6}He)^{13}O$ was about 150 keV. Hence there is no indication of any peaks with a width less than 500 keV.

B. $T=\frac{3}{2}$ states in ^{11}C and ^{11}B

The (p, t) and $(p, ^{3}He)$ reactions on ^{13}C were used to check the excitation energy and widths of the $T=\frac{3}{2}$ levels in ^{11}C and ^{11}B. The $\frac{1}{2}^{+}$ analogs of the ground state of ^{11}Be would not be expected to be strongly excited in these reactions whereas the $\frac{1}{2}^{-}$ analogs of the first excited state of ^{11}Be should

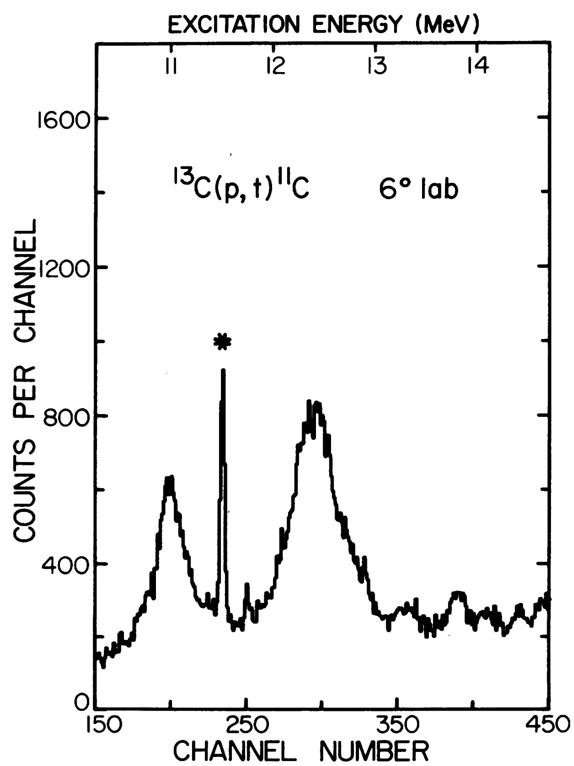

FIG. 2. A portion of the $^{13}C(p, t)^{11}C$ spectrum at 46.7 MeV and 6° (lab).

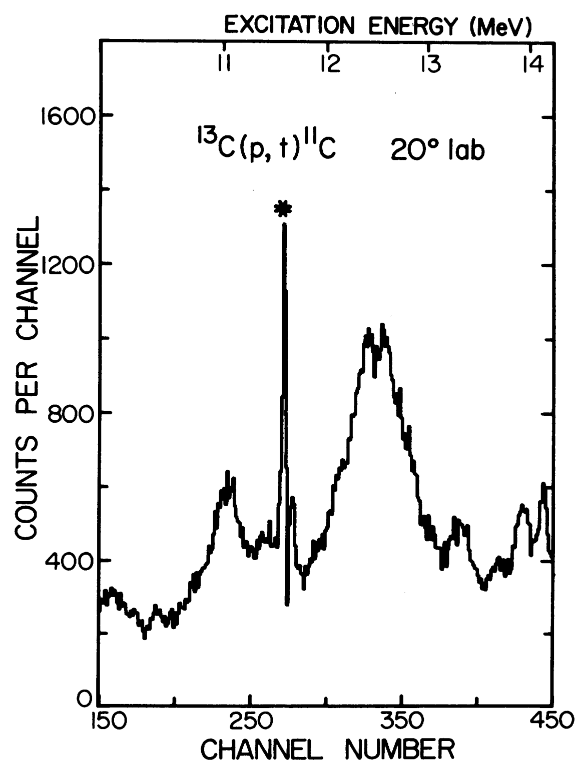

FIG. 3. A portion of the $^{13}C(p, t)^{11}C$ spectrum at 46.7 MeV and 22° (lab).

show up as a strong $L=0$ transition. The reactions were studied using a 200-μg/cm^2 ^{13}C foil target and a detection apparatus consisting of a wire counter backed by a plastic scintillator combination like the one used for the ^{14}N(^{3}He, ^{6}He)^{11}N experiment.

The ^{13}C(p, t)^{11}C experiment was performed at 46.7 MeV and laboratory angles of 6, 20, and 45°. The 6° spectrum is shown in Fig. 2. In this and the following two figures, the asterisk designates peaks from ^{12}C impurity in the target. The ^{12}C(p, t)^{10}C (3.353 MeV) peak near channel 240 served as the calibration. The $\frac{1}{2}^-$ $T=\frac{3}{2}$ level is centered on channel 300 and appears to be a smooth symmetric peak with the very large cross section expected for $L=0$ forward angles. An $L=0$ transfer is low relative to other L transfers at 20 and 45°, and at these angles there is a definite indication of the presence of other broad states. In particular the 12.65-MeV level observed by Jenkin, Earwaker, and Titterton[9] via a ^{10}B(p, α)^{7}Be resonance appears at 20° quite strongly so that the $T=\frac{3}{2}$ peak appears considerably broader as can be seen in Fig. 3. Only the 6° data were used for determining the level parameters. Table I gives a summary of the present results as compared to previous data on this region in ^{11}C.

The ^{13}C(p, ^{3}He)^{11}B reaction was studied at 40 MeV and angles of 6 and 22°. The spectrum at 22° can be seen in Fig. 4 to be somewhat obscured by multiple peaks from the ^{12}C(p, ^{3}He)^{10}B reaction which provided a calibration. A Gaussian fit to the $T=\frac{3}{2}$ state peak (near channel 300) gave very good agreement with previous measurements. The results on ^{11}B are also summarized in Table I.

III. DISCUSSION

The isobaric multiplet mass equation can be used to predict the mass excess of the $\frac{1}{2}^-$ state of ^{11}N. The prediction (25.15 ± 0.11 MeV) is in good agreement with the present result of 25.23 ± 0.10 MeV. A quartet based on the $\frac{1}{2}^+$ ground state of ^{11}Be would predict a mass excess of 24.98 ± 0.13 MeV, which shows that the two states ($\frac{1}{2}^+$ and $\frac{1}{2}^-$) would overlap. The possibility that both states are present in the 740-keV-wide peak can be ruled out on two grounds.

First of all, the $\frac{1}{2}^+$ would have a much smaller cross section than the $\frac{1}{2}^-$ for a pickup reaction like ^{14}N(^{3}He, ^{6}He)^{11}N. This is because of the small amount of the required $2s_{1/2}$ admixture in the target nucleus. The wave functions of True[10] for example have a $2s_{1/2}$ amplitude of 0.064. The measured cross section (0.50 μb/sr) at 10° is typical of (^{3}He, ^{6}He) on p-shell nuclei like ^{12}C, ^{13}C, and ^{16}O which range from 0.3 to 7.7 μb/sr. Secondly there is the question of the width of the peak which is consistent with the assumption of $\frac{1}{2}^-$ for the state. A $\frac{1}{2}^-$ state of ^{11}N at the measured mass excess would decay via an $l=1$, 2.2-MeV proton. The width of such a state would be so large as to appear very asymmetric with the lower-energy component much more attenuated by the Coulomb

TABLE I. Energy levels of ^{11}C and ^{11}B in the region of the $T=\frac{3}{2}$ states. All energies in MeV with errors in keV.

Nucleus	J^π, T	Previous measurements E_x	Previous measurements Γ	Present measurement E_x	Present measurement Γ
^{11}B	$\frac{1}{2}^+, \frac{3}{2}$	12.55 ±30	0.235±27 [a]	Not observed	
	$\frac{1}{2}^-, \frac{3}{2}$	12.91 ±20	0.230±65 [a]	12.91±30	0.260±50
	$\frac{3}{2}$	14.33 ±20	0.255±36 [a]	Not observed	
^{11}C	$\frac{1}{2}$	11.032± 5 [b]		11.03±30	0.300±60
	$\frac{1}{2}^+, \frac{3}{2}$	12.17 ±50	0.290±50 [c]	Not observed	
	$\frac{1}{2}^-, \frac{3}{2}$	12.48 ±80	0.566±60 [d]	12.48±40	0.540±60
	$\frac{7}{2}^+, \frac{1}{2}$	12.65 ±20	0.370 [c]	Unresolved	
		13.33 [b]		13.33±60	0.270±80
		13.90 ±20	0.450 [b]	13.90±40	0.150±50
		14.07 ±20	Broad [b]	14.07±40	0.135±50

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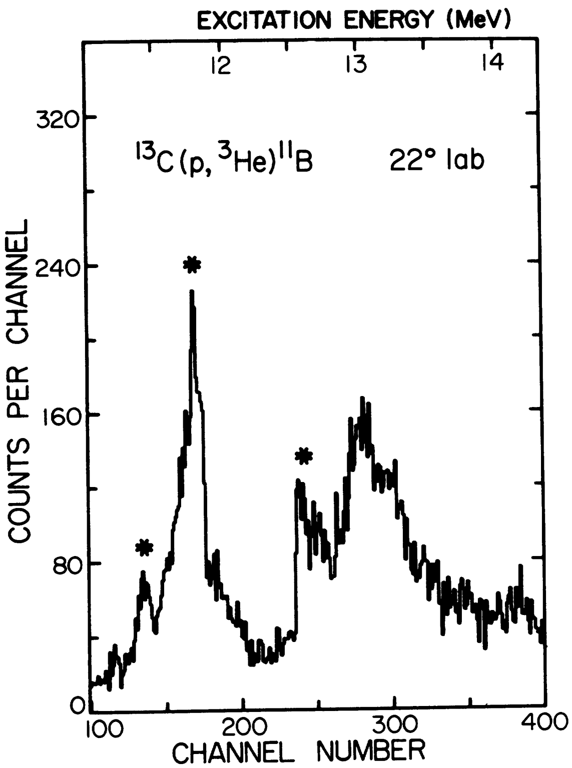

FIG. 4. A portion of the $^{13}C(p,^3He)^{11}B$ spectrum at 40 MeV and 22° (lab).

and centrifugal barrier. A continuum calculation was made by Bertsch[11] in an attempt to produce this shape theoretically. A Woods-Saxon well plus centrifugal and Coulomb barrier was adjusted such that the probability of locating protons from the continuum inside the nucleus has its maximum value at 2.2 MeV. The resulting probability distribution appears somewhat broader than the observed peak, indicating a spectroscopic factor for the state of 0.7 ± 0.1. This value is in good agreement with spectroscopic factors calculated with the wave functions of Cohen and Kurath[12] (0.66) or of Hauge and Maripuu[13] (0.60). These wave functions do not include $2s_{1/2}$ particles hence cannot be used to give a spectroscopic factor under the assumption of $\frac{1}{2}^+$ for the state. However, the same continuum calculation for the width is incapable of producing a peak for a $2s_{1/2}$ shell proton with any reasonable Woods-Saxon potential. Since the spectroscopic factor is certainly quite large, this indicates a $\frac{1}{2}^+$ state would be too broad to be observed even if it could be made by the ($^3He, ^6He$) reaction.

IV. CONCLUSIONS

The $\frac{1}{2}^+$ and $\frac{1}{2}^-$ level in ^{11}N, which would be the mirrors of the ground and first excited states of ^{11}Be, would be broad and overlapping. A peak in the $^{14}N(^3He, ^6He)^{11}N$ reaction spectrum is interpreted to be the mirror of the $\frac{1}{2}^-$ state in ^{11}Be since it has a width consistent with a $l = 1$ decay and a spectroscopic factor calculated with p-shell wave functions. A $\frac{1}{2}^+$ state could not be formed with a comparable cross section and would display a much greater width. In any case, the peak is shown to behave with the kinematics of a two-body final state reaction and is therefore attributed to ^{11}N.

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